The asteroid-comet continuum

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The asteroid-comet metamorphosis

- Pick an *inactive* C or D asteroid
- Peal off the first 10 meters with a rake
- Change telescopes

The asteroid-comet metamorphosis

- Observe cometary activity

Dark asteroids and comets : Tweedledum and tweedledee*

*Blanc bonnet et bonnet blanc

The asteroid-comet continuum

1. The meteorite evidence

2. The Stardust mission ground truth

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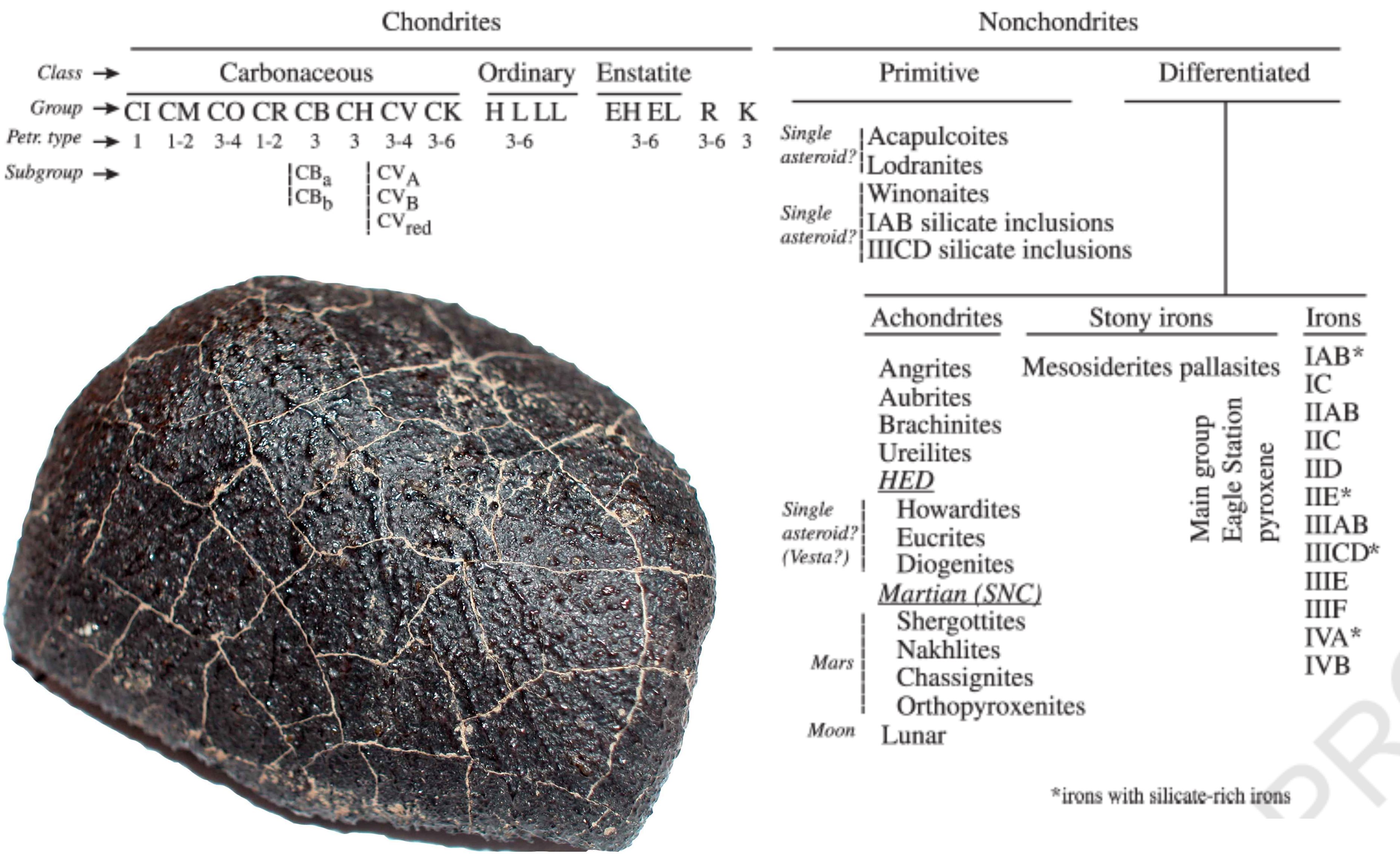
4. Discussion

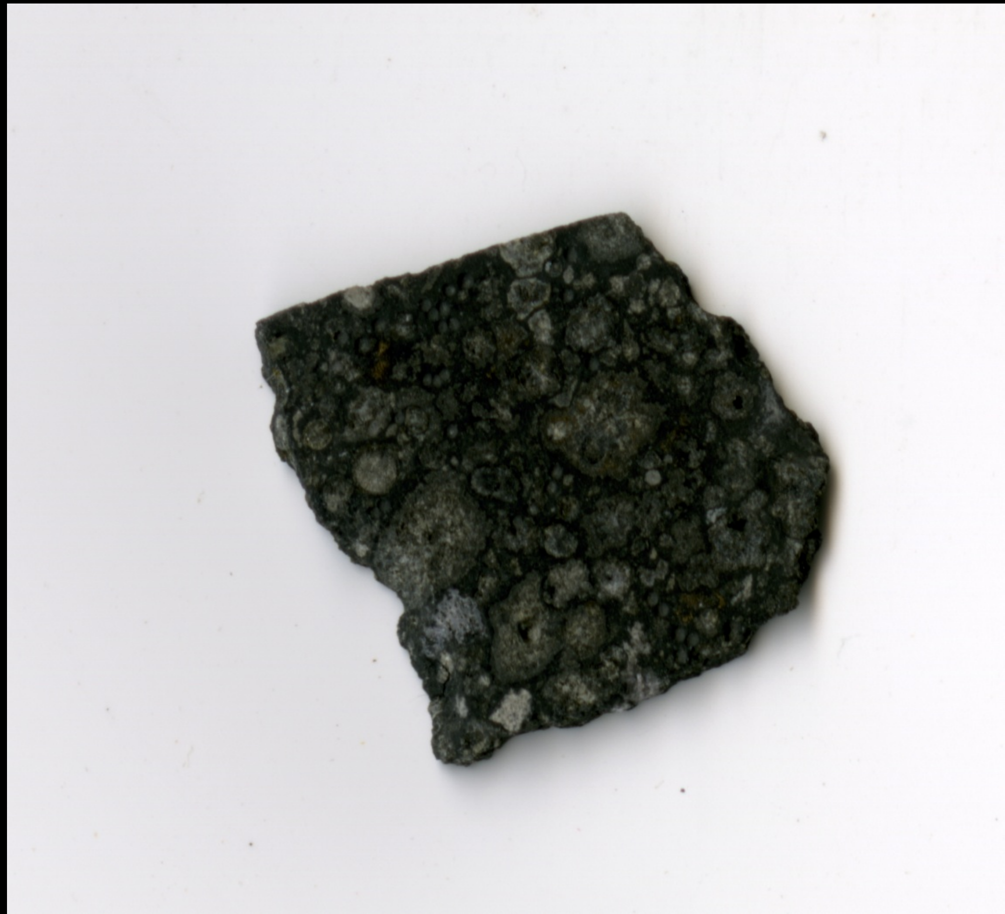
5. Conclusions



Meteorites are complex extraterrestrial *rocks*

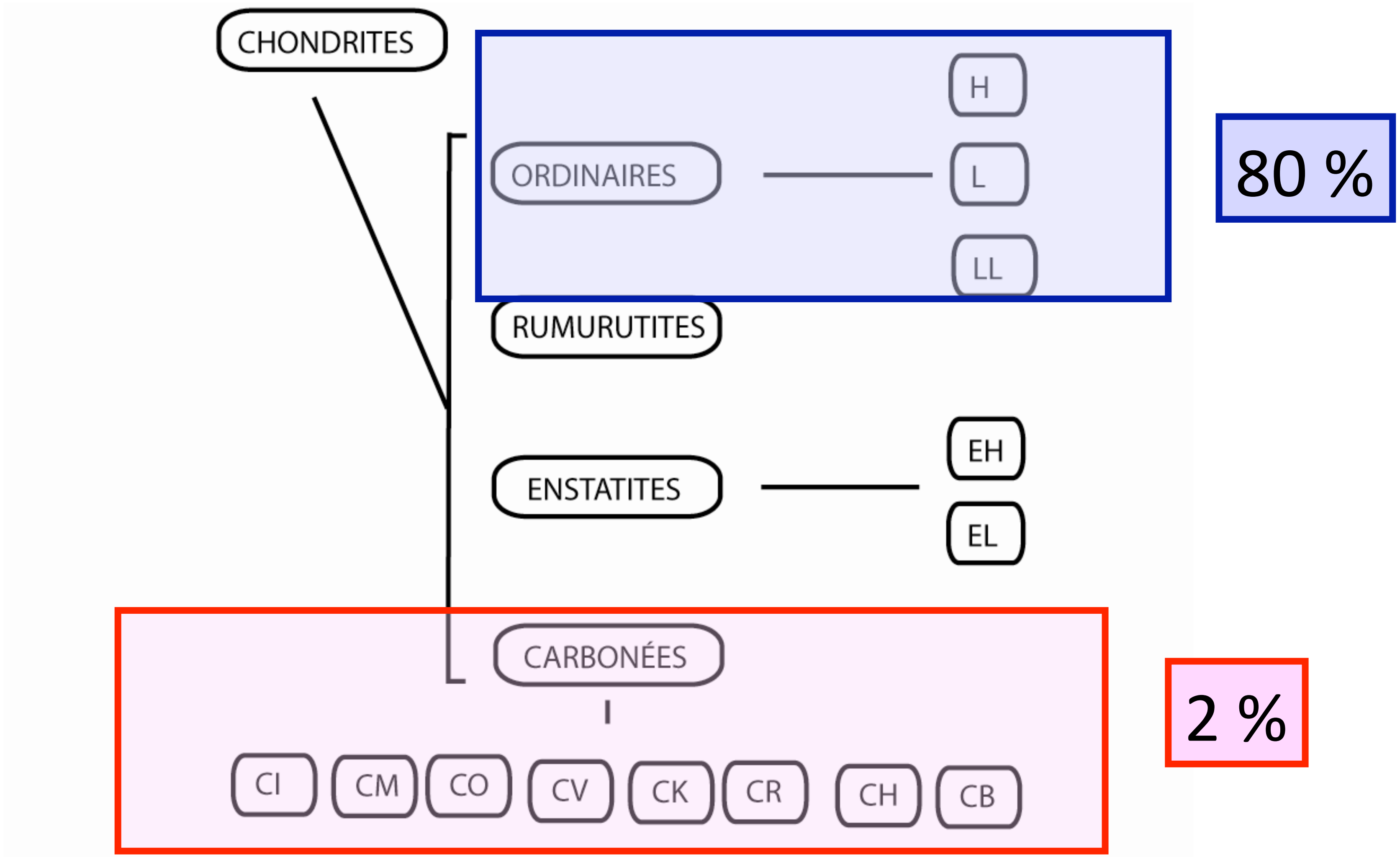
Differentiated & primitive meteorites

PALLASITE (DIFFERENTIATED)



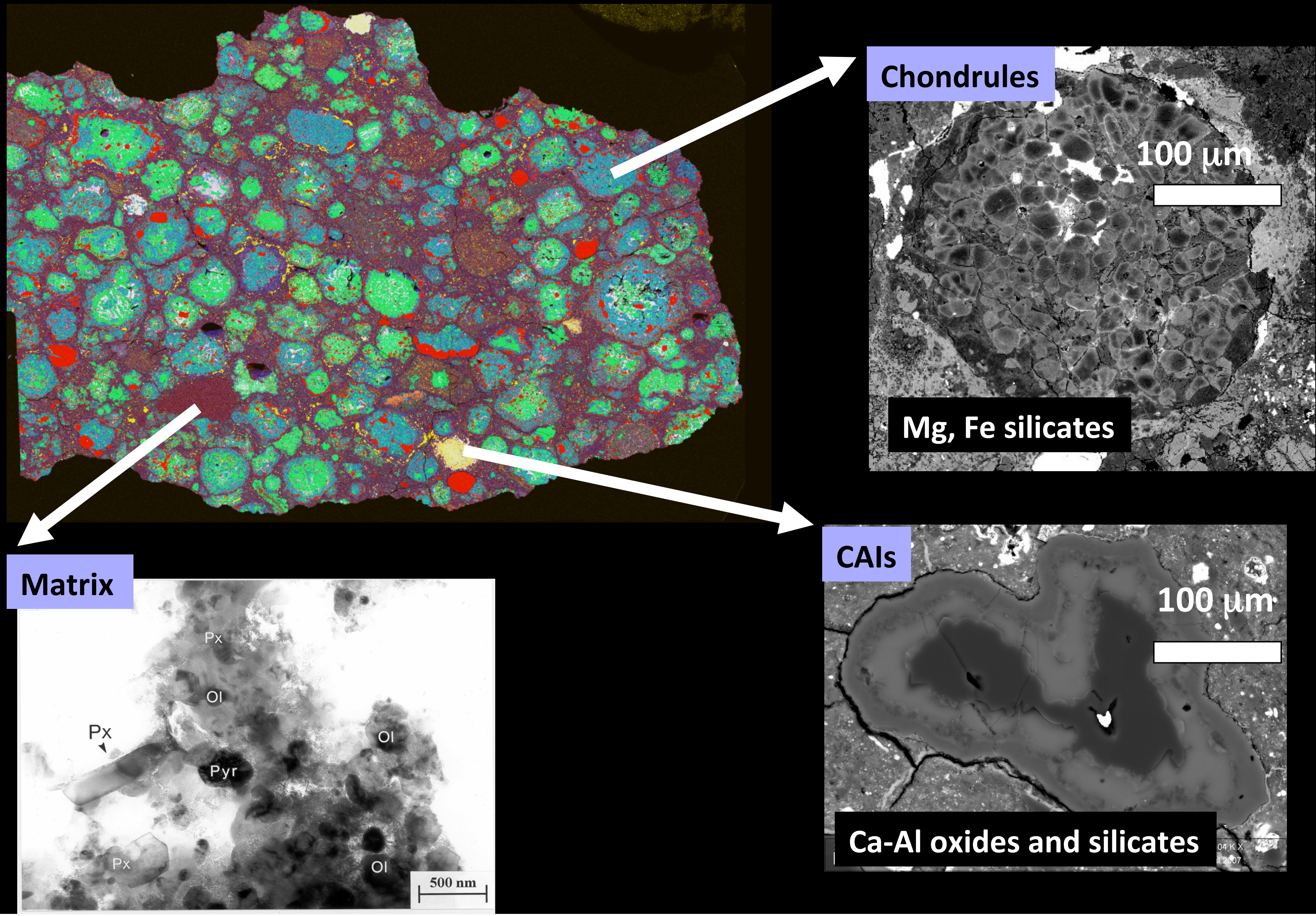
CHONDRITE (PRIMITIVE)

Many different chondrites' groups

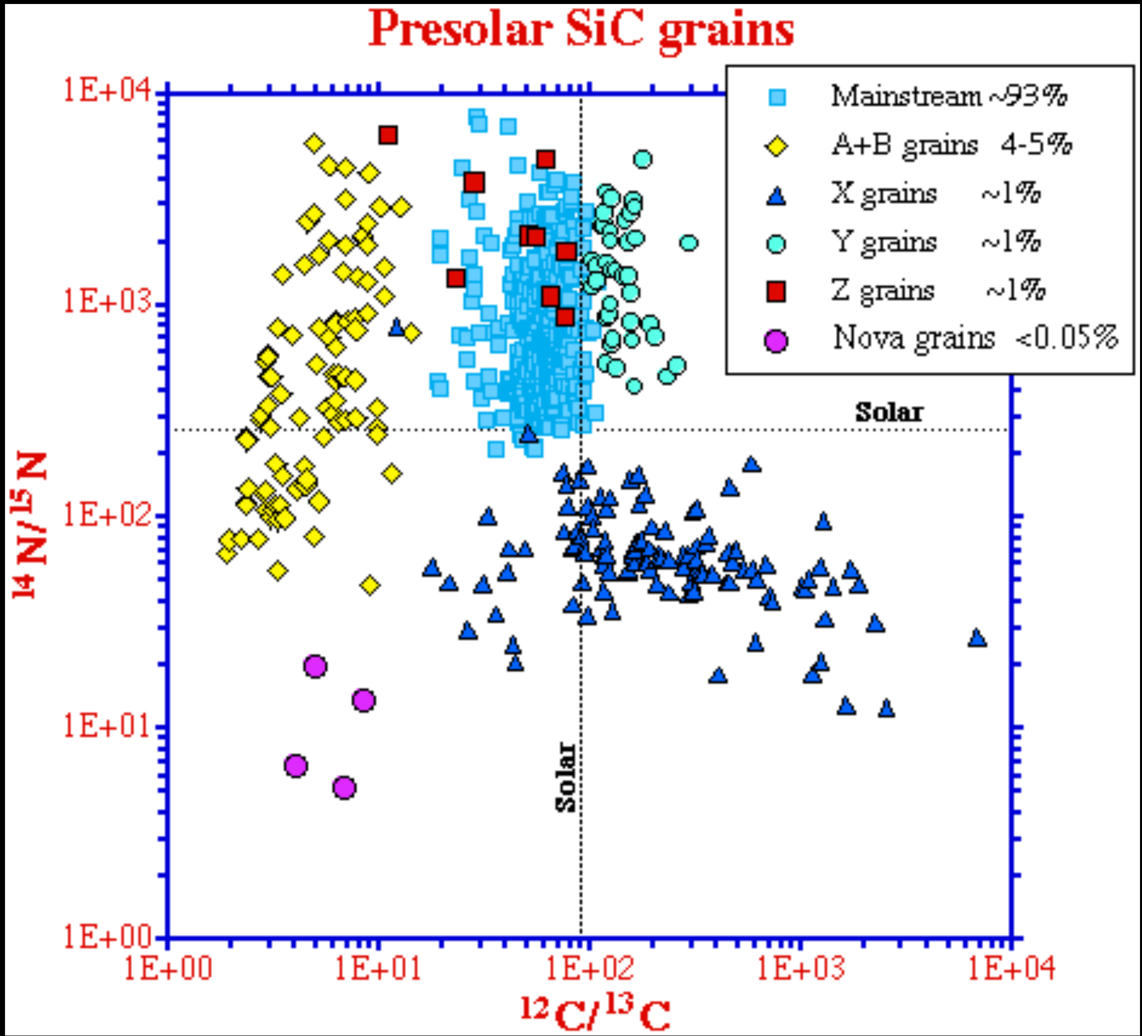


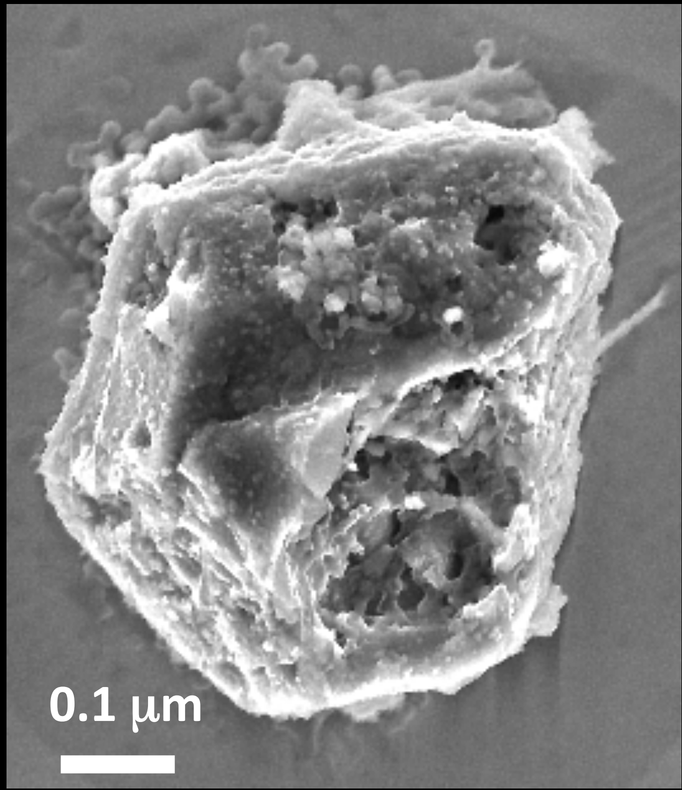
Carbonaceous chondrites linked to C and D (dark) asteroids

Chondrites' components



Presolar grains in the matrix





Nittler 2005

400 ppm in the most primitive chondrites

Some carbonaceous chondrites are rich in water

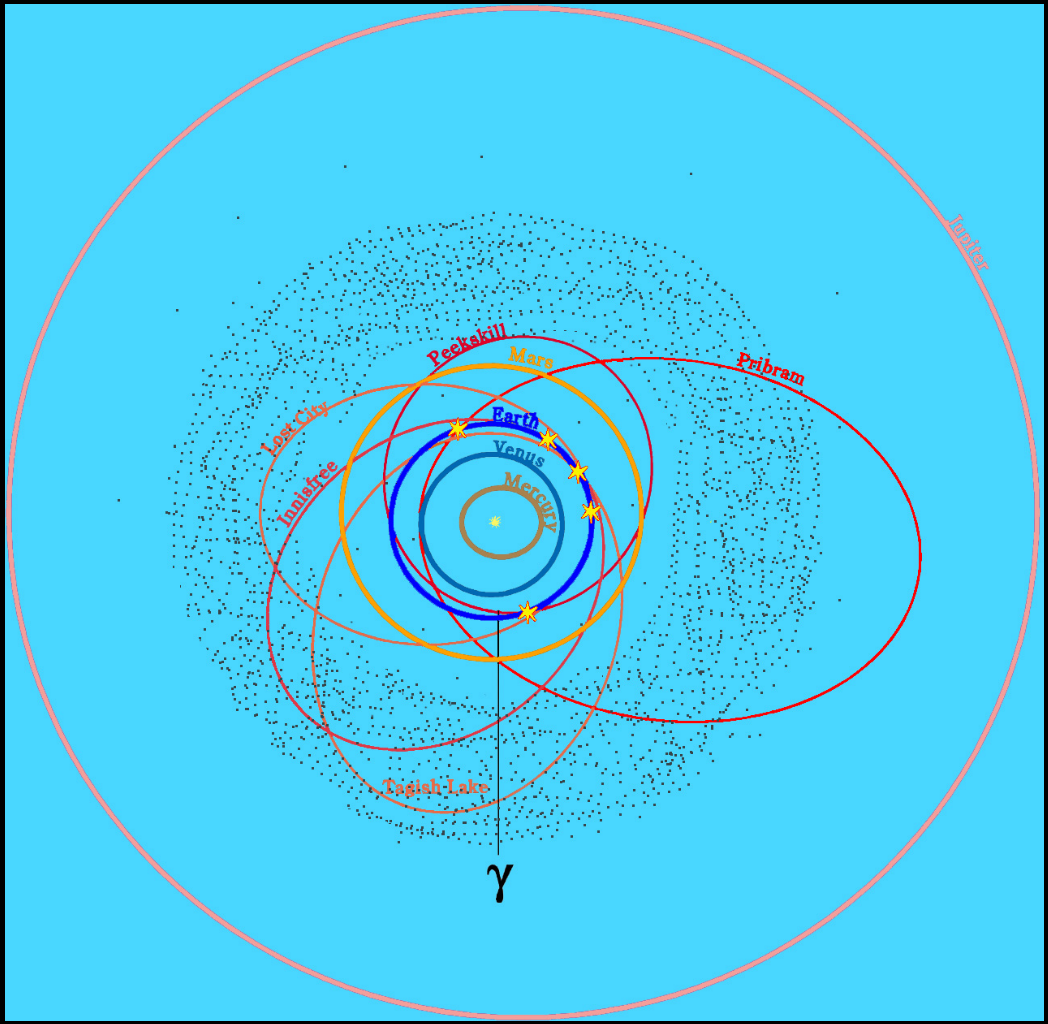
- Orgueil (CI1): 15 wt% H_20
- Murchison (CM2): 5 wt% H_20

They contain secondary minerals (clays & carbonates)made during hydrothermal alteration on their respective parent-bodies

<u>The water/rock ratio is roughly one (e.g. Young 2001)</u>

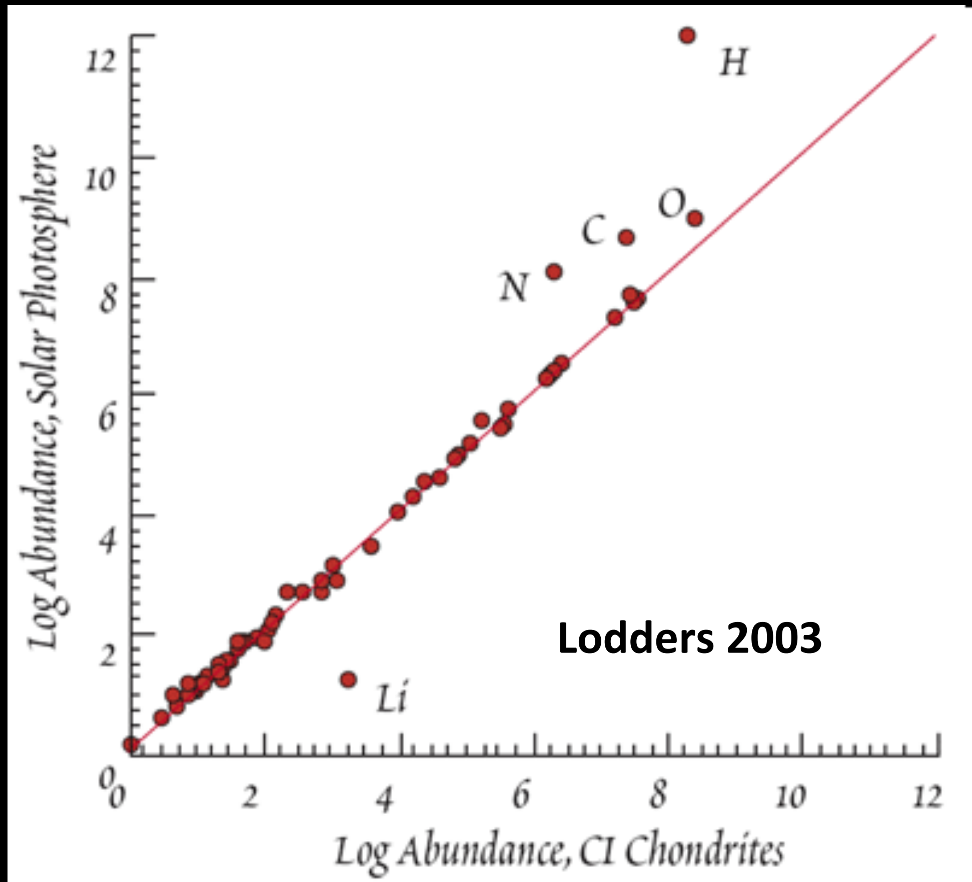
Assuming CCs come from dark asteroids, what is the difference between an asteroid which contains 50 % ice and a comet that contains 50 % dust (e.g. O'Hearn 2005) ?

Chondrites' orbits



The carbonaceous chondrite Tagish Lake is on asteroidal orbit

The Orgueil meteorite



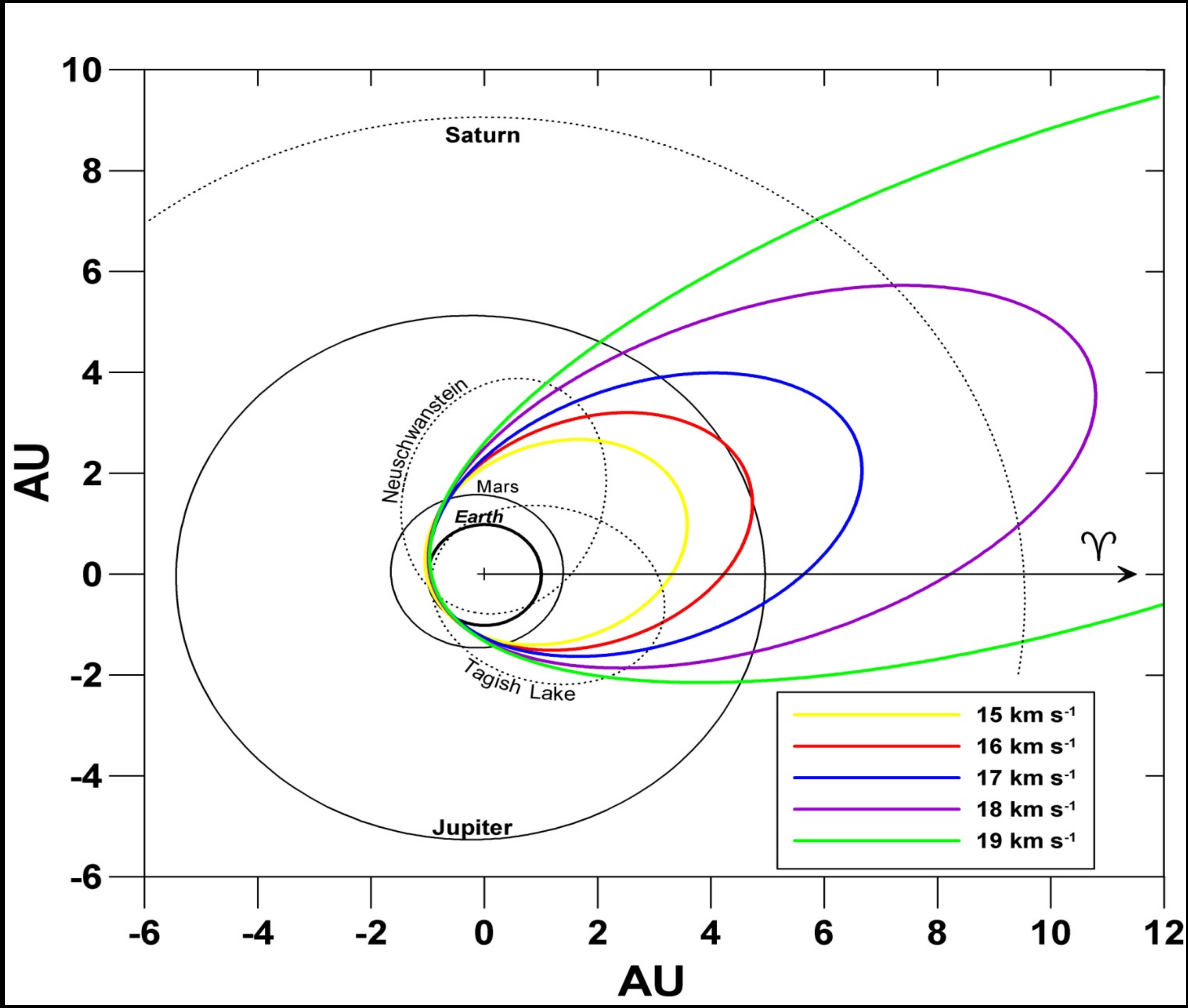
Chemically identical to the Sun

Heavily hydrothermally altered (clays & carbonates)

Visual observations of Orgueil – may 1864

Gounelle, Spurny & Bland *MAPS* 2006

Cometary origin of Orgueil



Gounelle, Spurny & Bland *MAPS* 2006

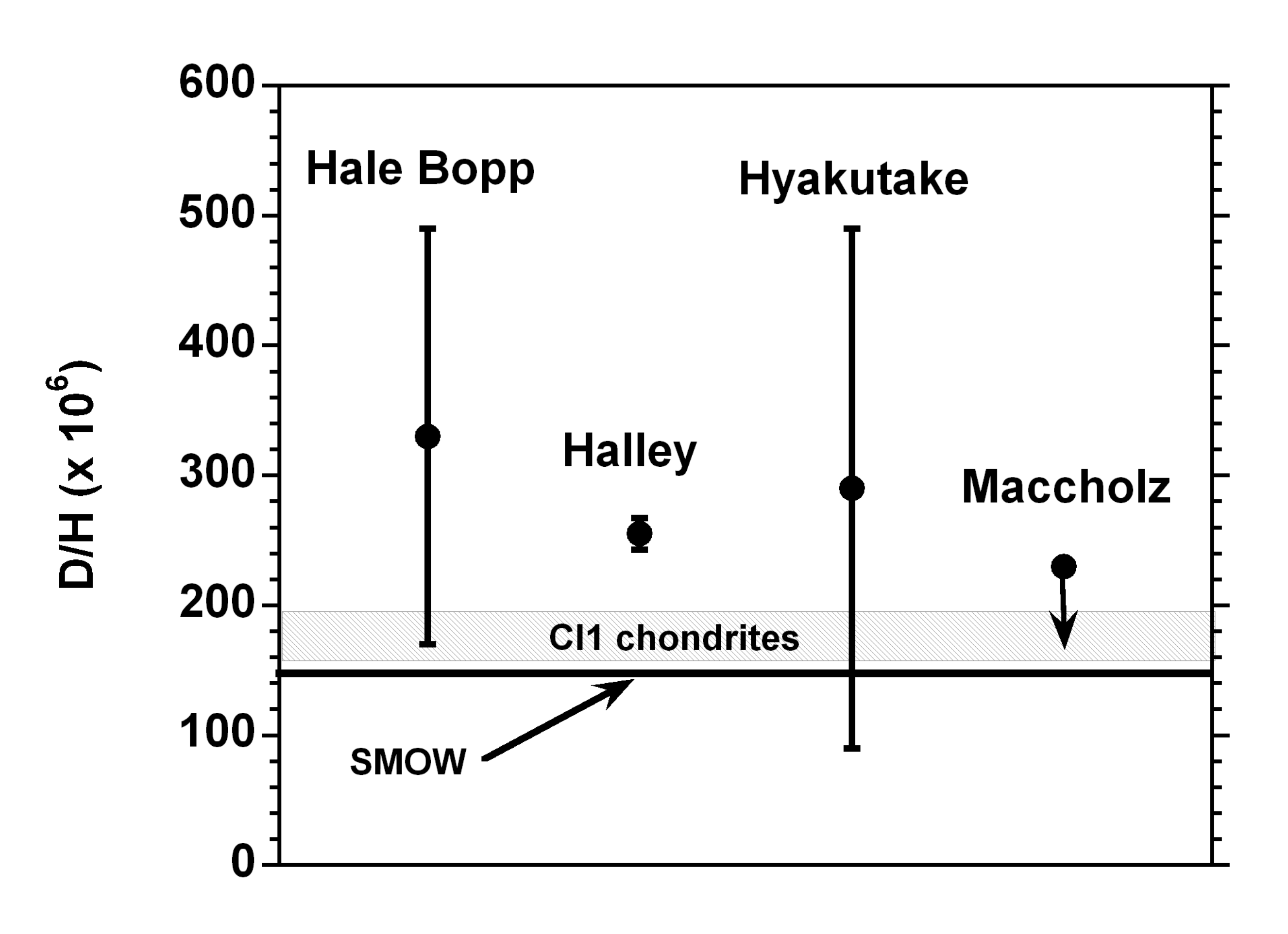
Continuum between asteroids & comets

> comparison to CI1 chondrites. In any case, independent of the possible cometary origin of Orgueil and the results yielded by the Stardust mission, a continuum between asteroids and comets is expected in our solar system, smoothing the possibly provocative proposition that five cometary meteorites are already present within terrestrial museums.

Some carbonaceous chondrites come from comets, other from dark asteroids

Gounelle, Spurny & Bland *MAPS* 2006

A lingering problem : the water D/H ratio of Oort cloud's comets



Data from literature – 2σ error bars

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Stardust expectations

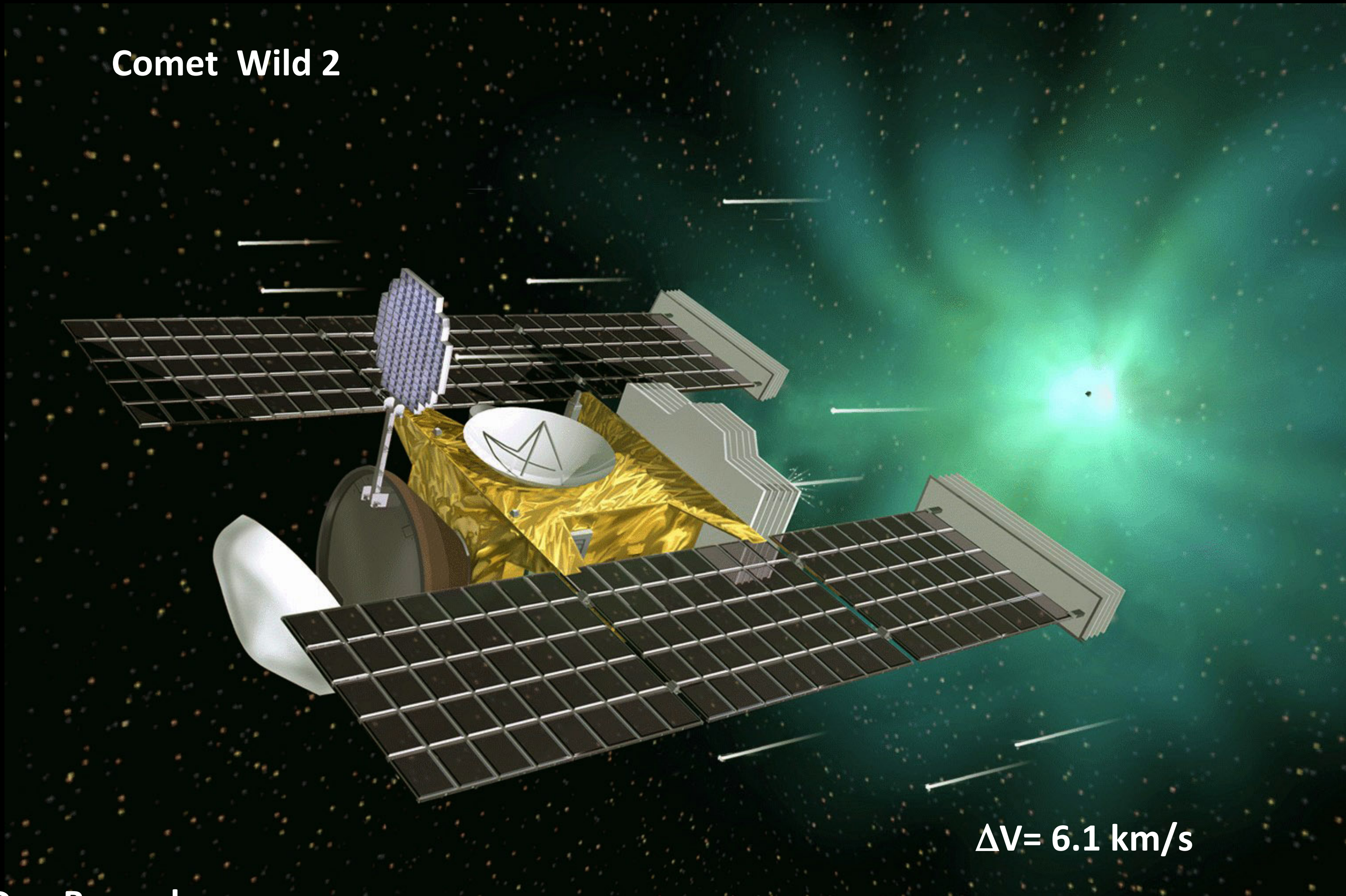
- Fine-grained aggregates like ISM dust (see IDPs)
- High abundance of presolar grains
- Large deuterium excesses

because

- Comets were supposed to be more "primitive" than asteroids

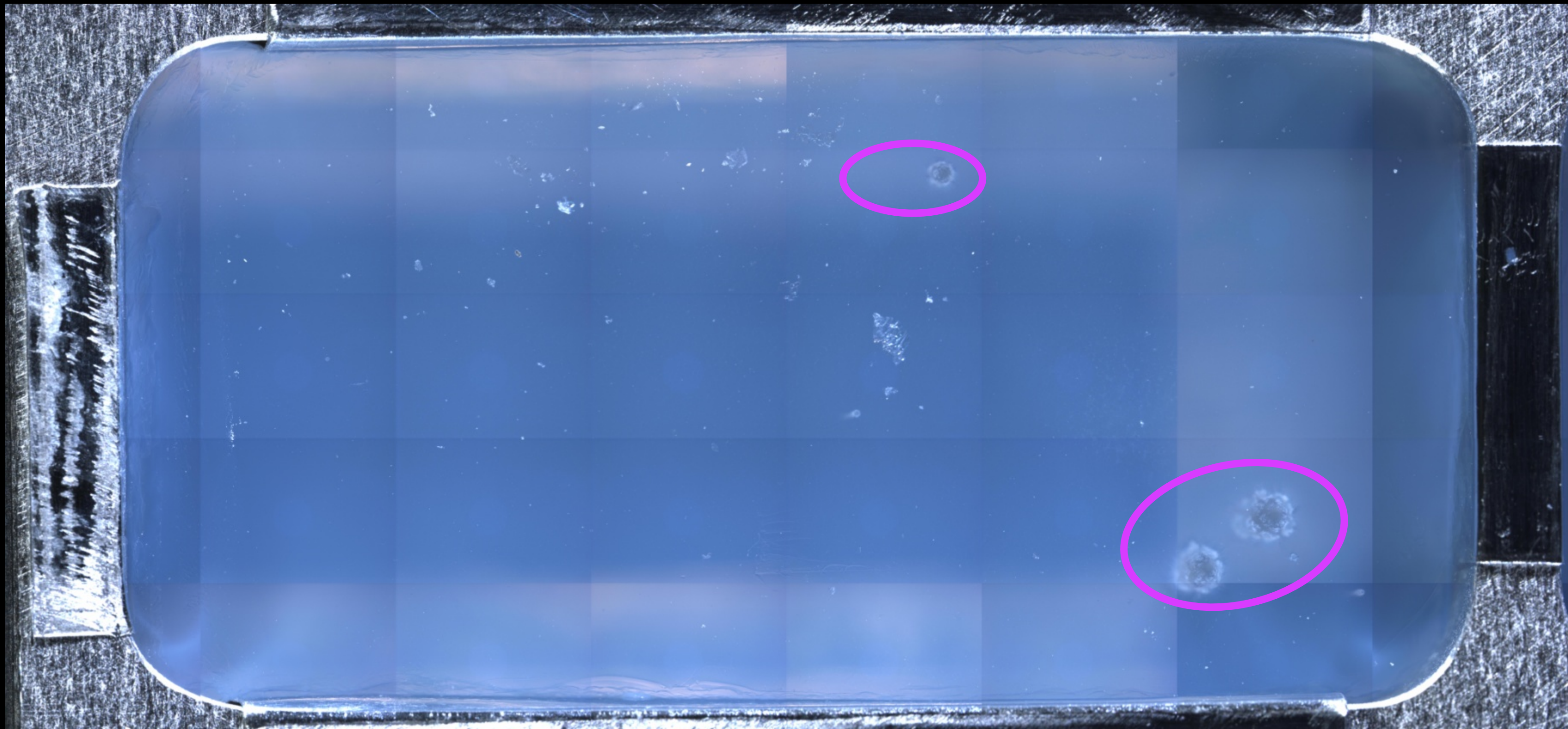
1. Formed further away than asteroids (no high T processing)
2. Best record the ISM (D enrichments)
3. Immune to geological processing

Sample collection (January 2nd 2004)



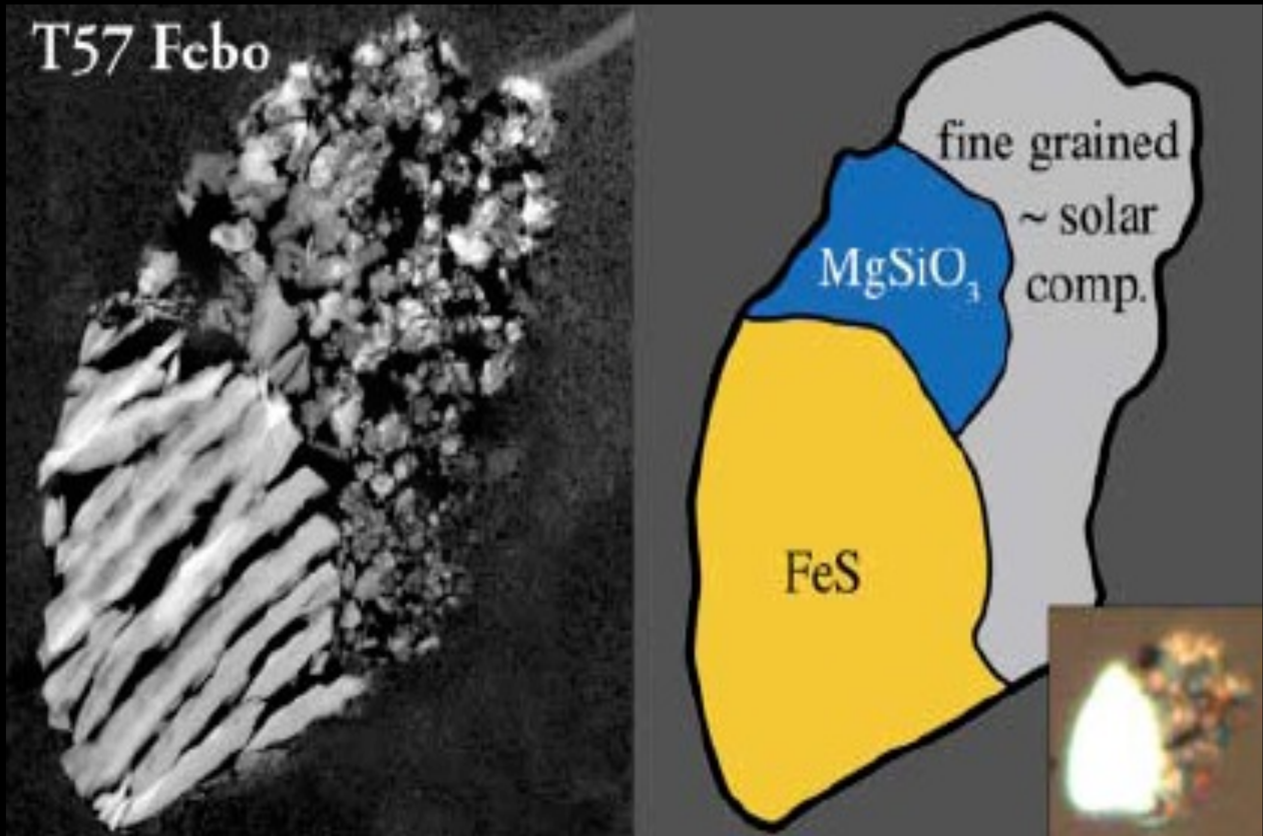
PI: Don Brownlee

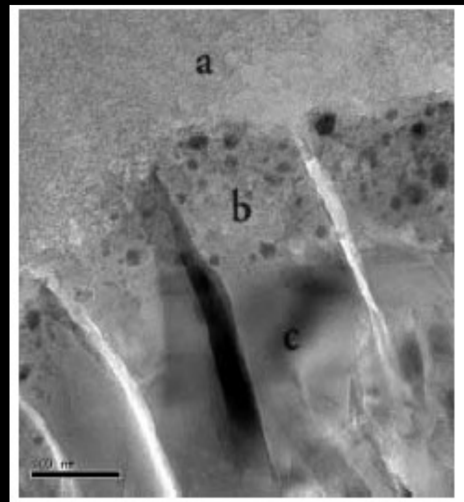
Stardust success!



~ 1000 grains with sizes > 5 μm
~ 100 μg of cometary dust

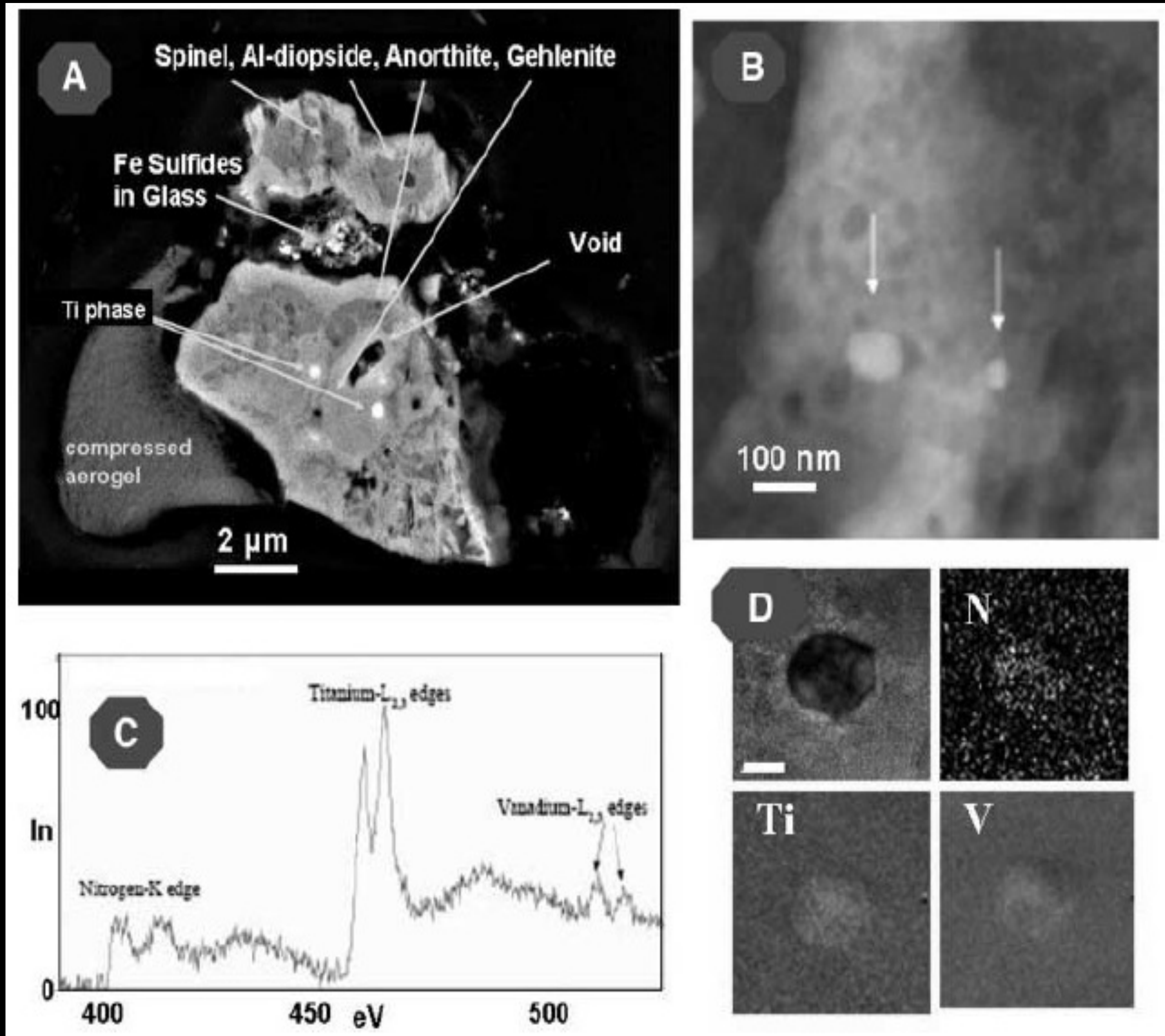
Basic mineralogy





Olivine, pyroxene, sulfides, metal
Similar to what is found in primitive meteorites

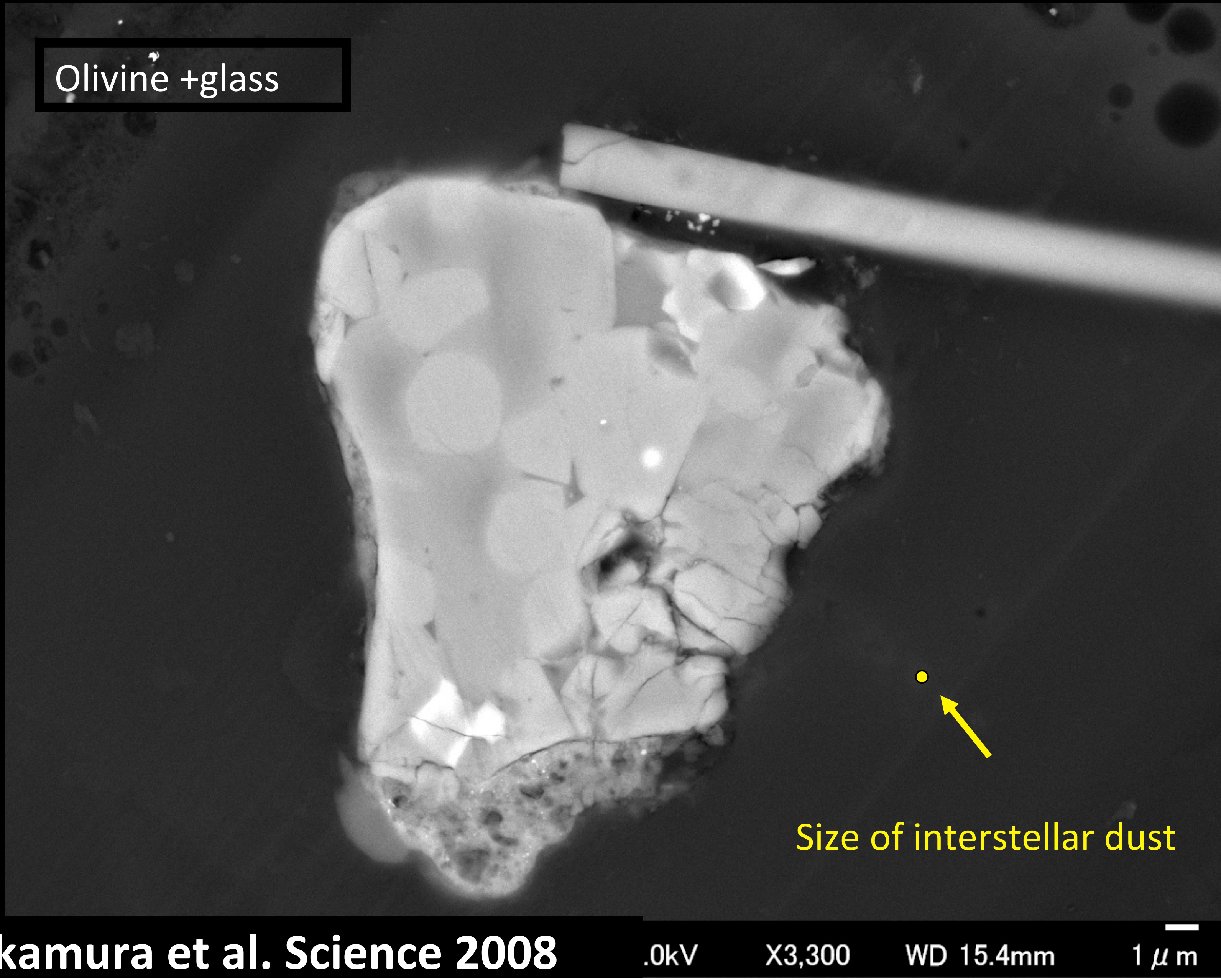
CAIs in comets



Zolensky et al. 2006

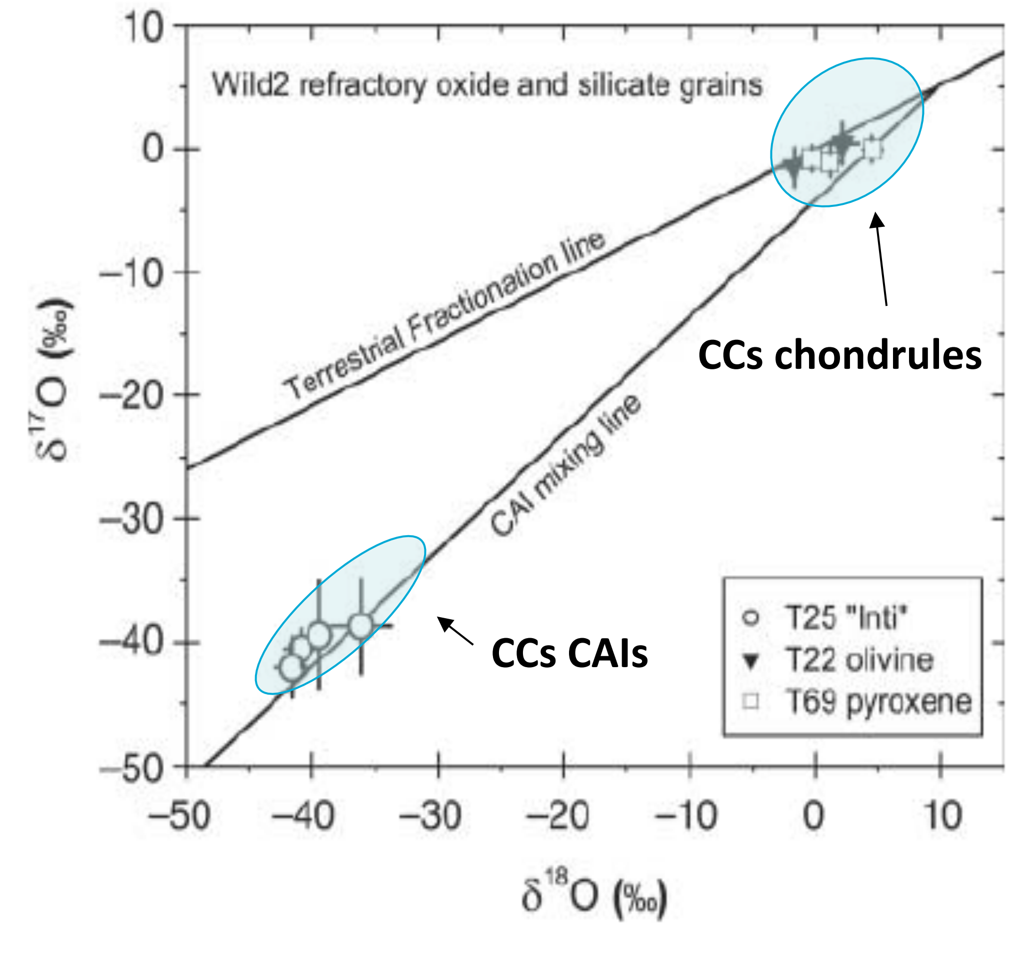
High T phase - important radial mixing in the Solar System

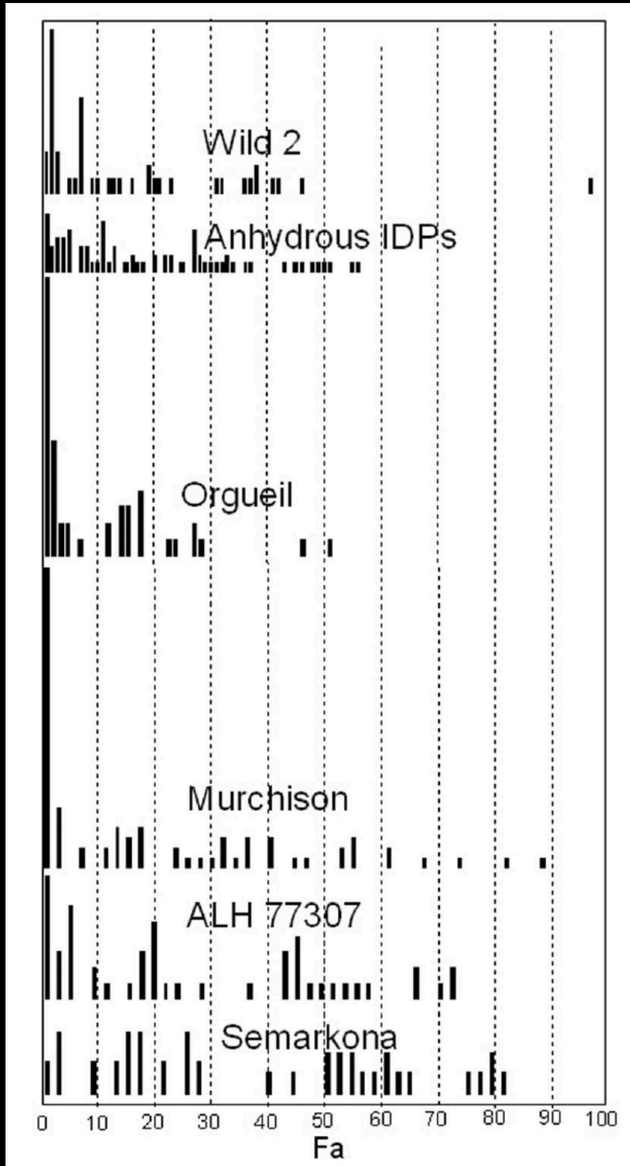
Chondrules in comets



Nakamura et al. Science 2008

More similarities with carbonaceous chondrites

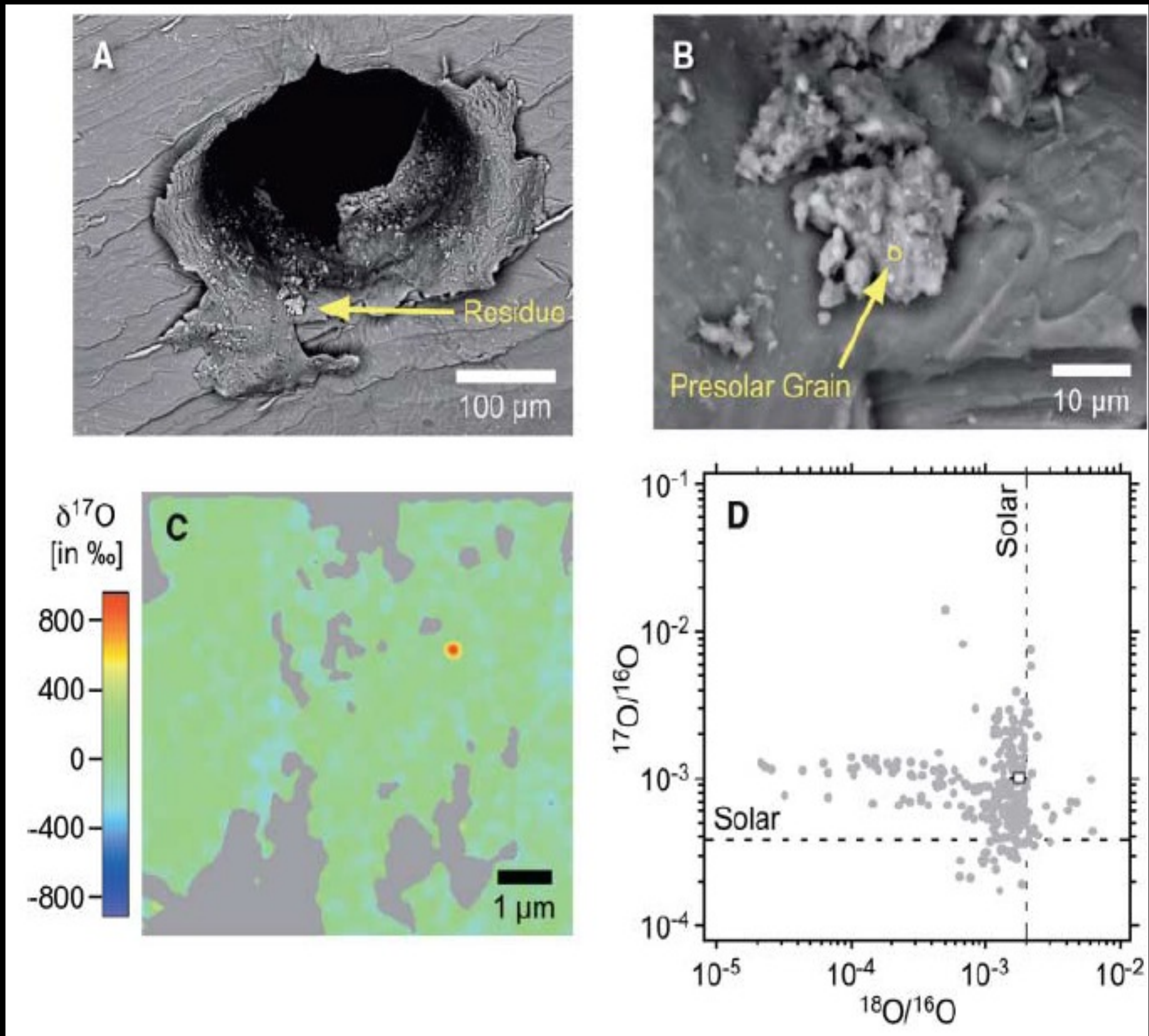




McKeegan et al. 2006
Zolensky et al. 2008

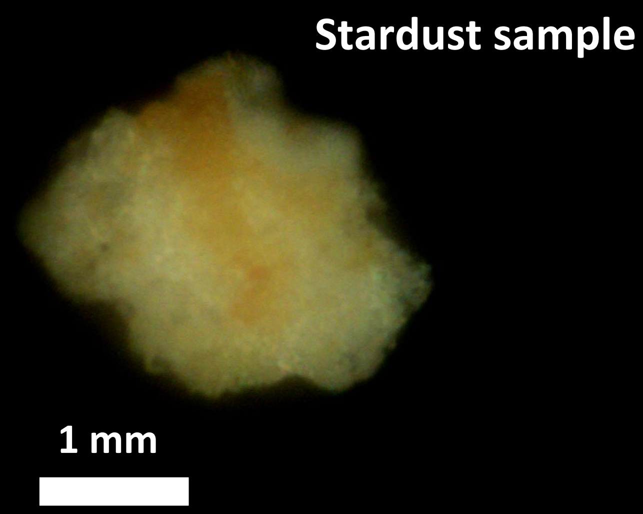
Very few presolar grains

McKeegan et al. 2006



A few 10s of ppm < chondrites

Stardust summary



Wild 2 dust was processed in the solar system: NOT primitive interstellar matter

Wild 2 dust looks alike carbonaceous chondrites : Continuum between dark asteroids & comets

Important radial mixing between the inner & outer solar system

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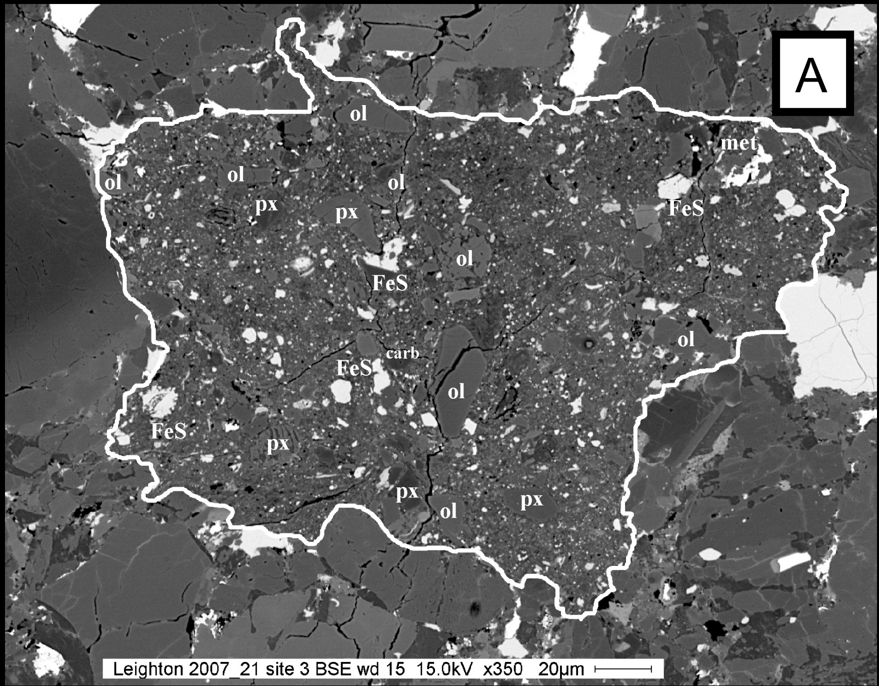
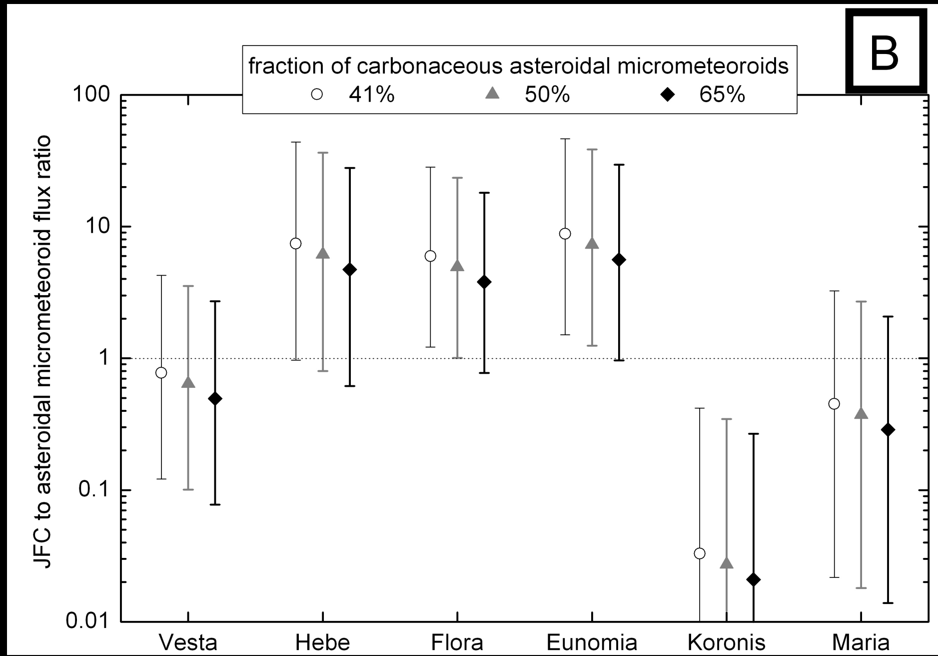
Xenoliths (clasts) in meteorites





There is a "unique" population of xenoliths in ordinary chondrites and howardites (Briani et al. Submitted A)

Xenoliths are expected to be a mixture of cometary and asteroidal dust (Briani et al. Submitted B)

No difference between dark asteroids and comets

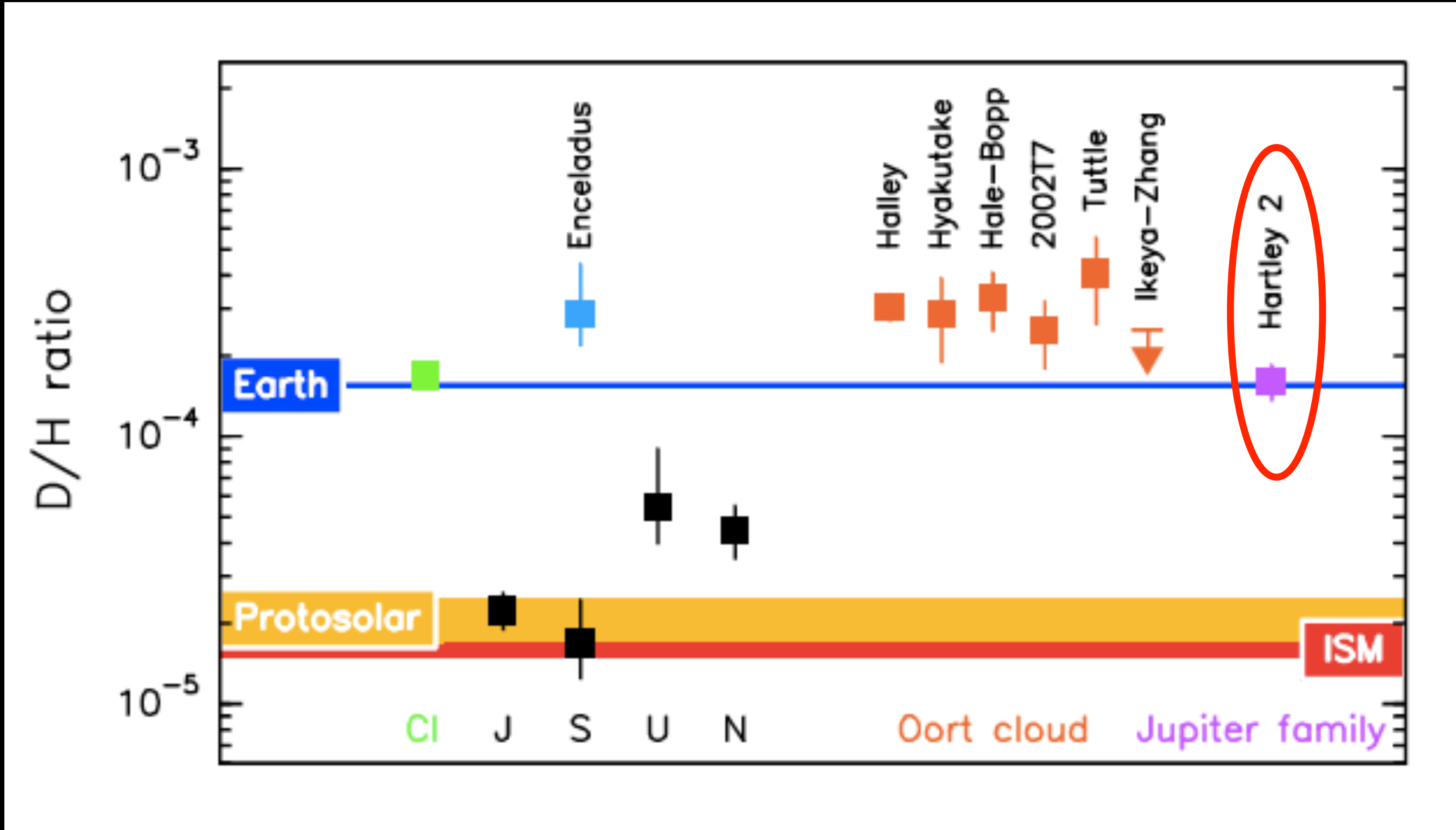
Antarctic micrometeorites (AMMs)

Dobrica et al *MAPS* 2008

AMMs have sizes 30-300 µm
Collected in Antarctica (Maurette, Duprat)
200 µm objects dominate the flux
Sample the zodiacal cloud

200 µm dust in the zodiacal cloud is cometary (Nesvorny et al. 2010)
As AMMs are similar to carbonaceous chondrites (assumed to be asteroidal), it indicates a continuum between asteroids and comets

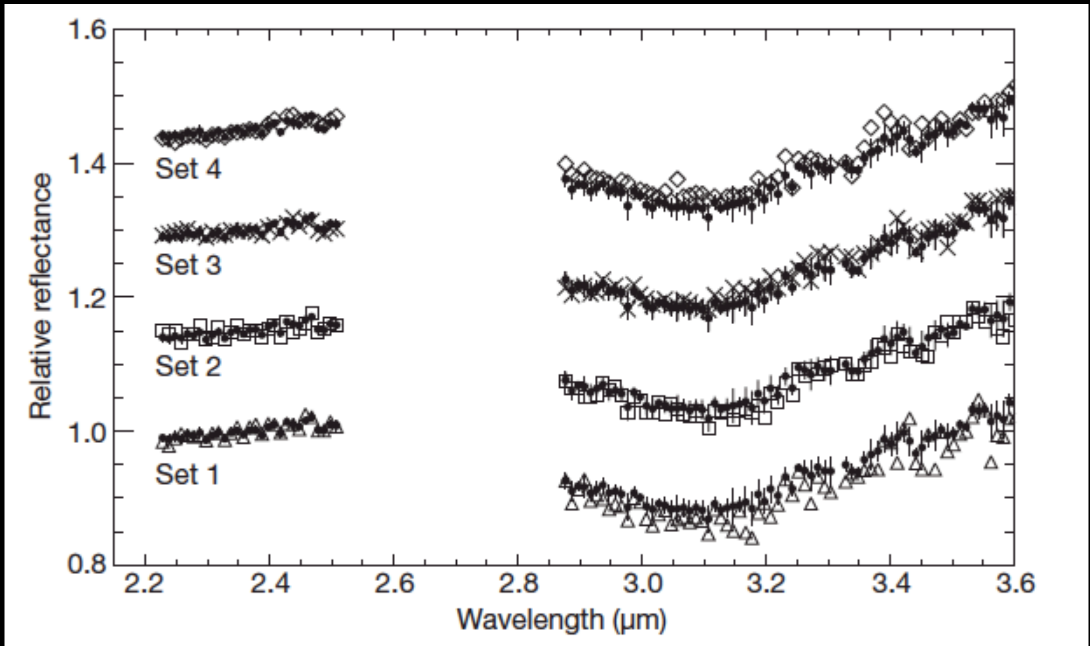
The water D/H ratio of JFCs



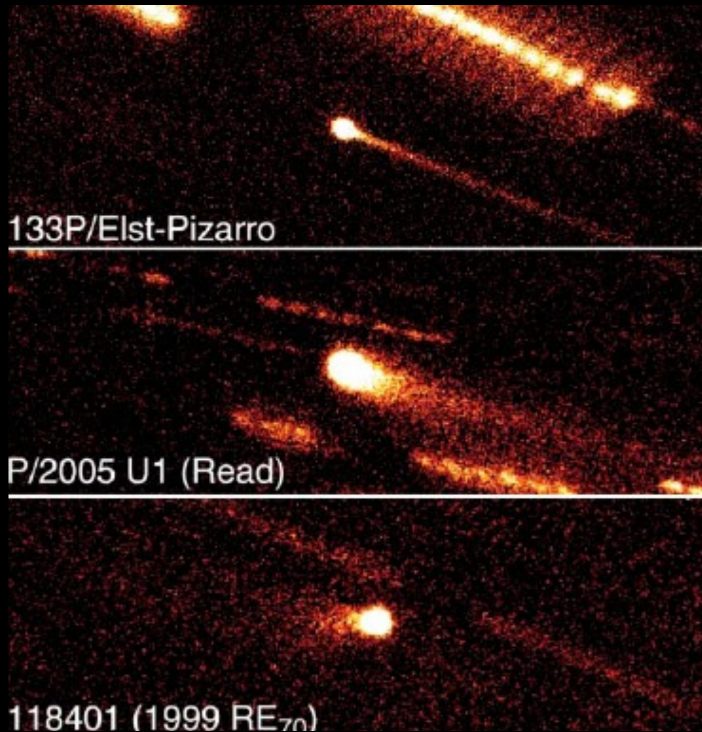
Hartogh et al. 2011, Nature in press – see Bockelée-Morvan's talk

The hydrogen isotopic composition of JFC(s) is identical to that of Orgueil…

Water ice on asteroids



Campins et al. Science 2010



Hsieh & Jewitt Science 2006

Recent remodeling of the surface
Collision and/or splitting acted as a rake…

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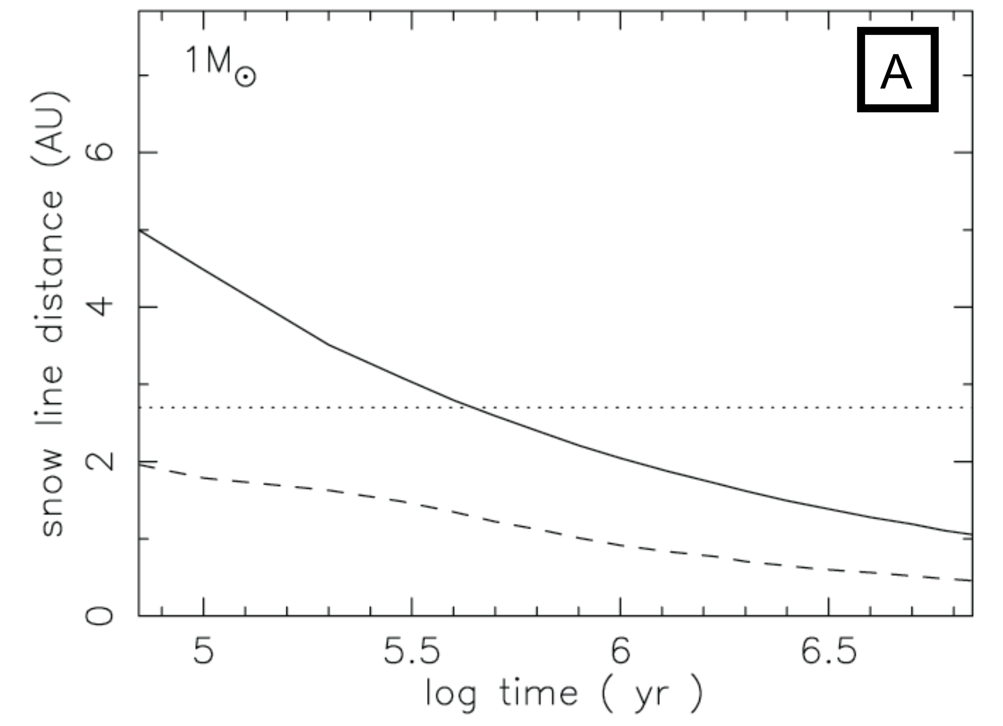
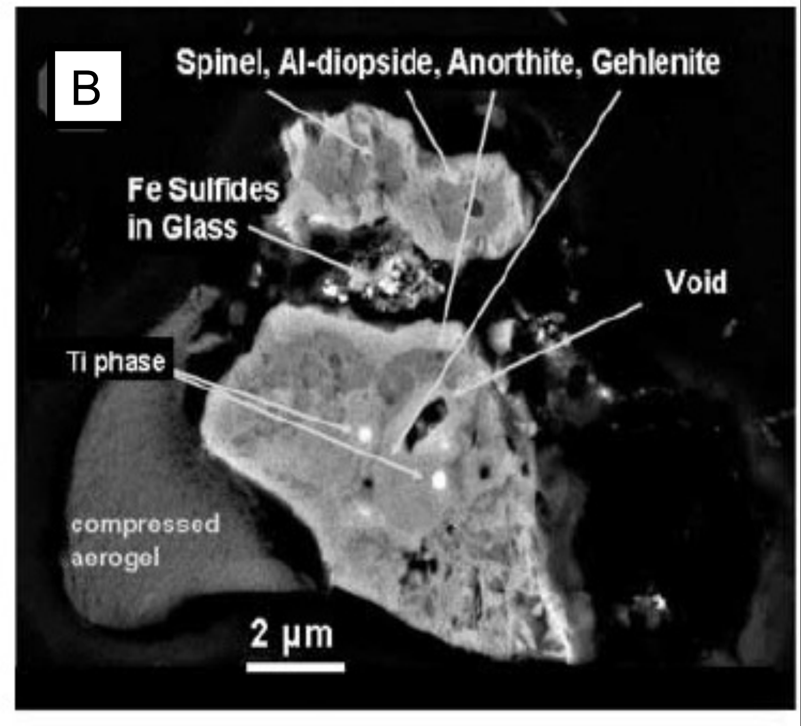
Why a continuum ? Transport of components





Kennedy & Kenyon 2008

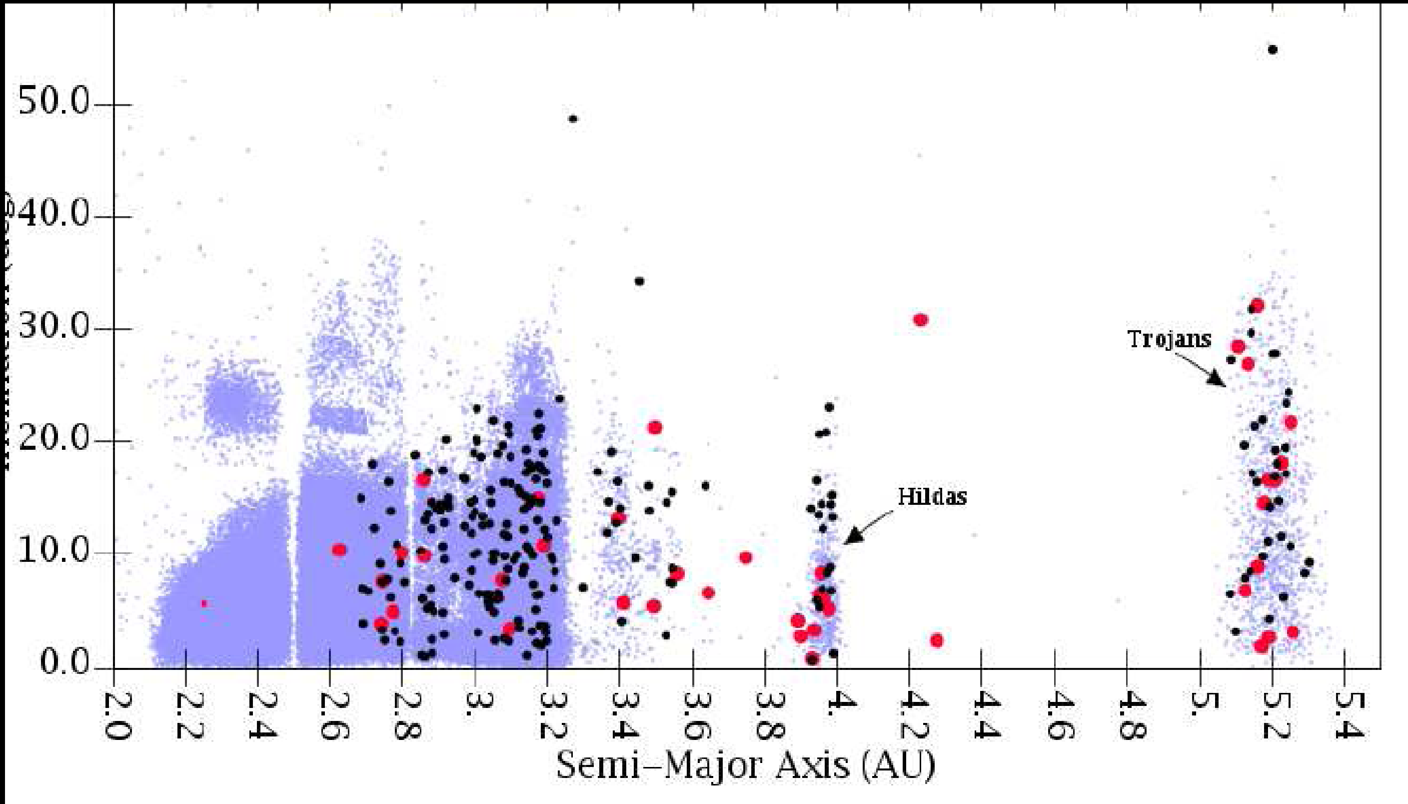
Zolensky et al. 2006

1. Extensive transport of chondritic components in the disk (B)

2. Snow line position variations with time (A)

Bodies can have accreted components from a wide range of heliocentric distances

Why a continuum ? Transport of small bodies



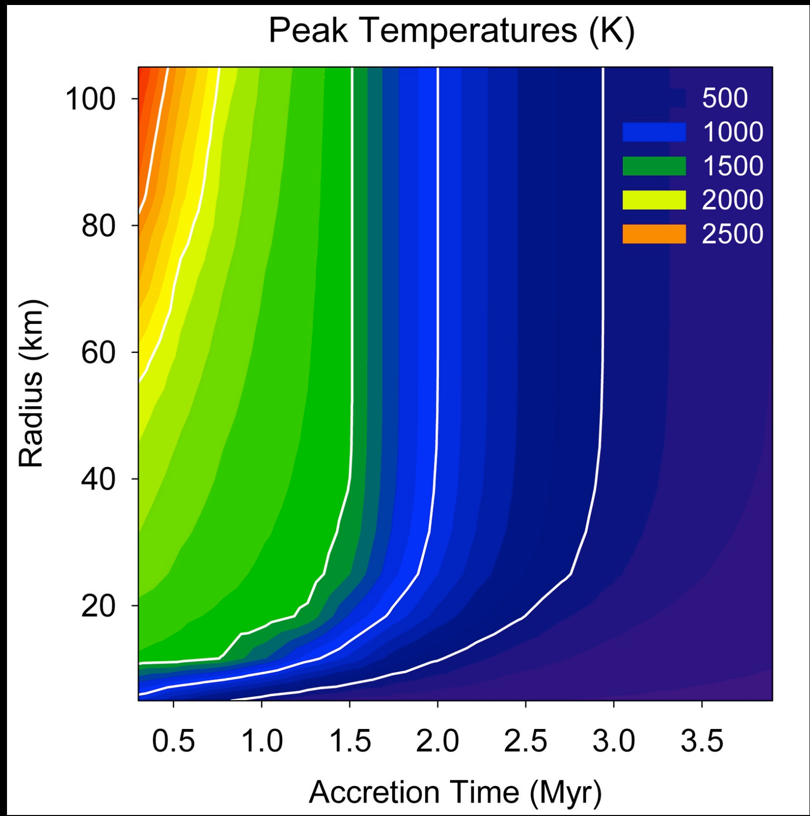
During the LHB, comets were implanted in the asteroid belt. Now D asteroids.

See also Walsh et al. 2011

Levison et al. 2009

Hydrothermal alteration in water-rich bodies

Young 2011



Little hydrothermal alteration in Wild 2

Some (?) secondary minerals (phyllosilicates, carbonates) in Tempel 1

Same is true for asteroids

Variable amount of aqueous alteration in comets and asteroids

Gounelle et al. 2008 in The Solar System beyond Neptune (Eds Barrucci et al.)

Some *observational* differences

- Spectra
- Albedo
- Density (0.8-1.3 vs. 0.5 -1.2 g/cm^3)

- All can be ascribed to different sizes and environments over the last 4.5 Gyr
  - Inner solar system vs. outer solar system

    Collision frequency, micrometeorite flux, GCR flux…

- This is a difference in breeding, not in genes…

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Conclusions

- Comets & dark asteroids are identical in *nature*

- Comets and dark asteroids are sampled by carbonaceous chondrites, AMMs…

- The comet-asteroid continuum arises from intense transport of chondritic components (CAIs, chondrules) and small bodies

- The *observational* differences between comets and dark asteroids are due to a different environment/history: residence in the inner/outer solar system

- Depending on size, accretion times etc… water-rich bodies have endured varying amounts of hydrothermal alteration

- Primitive samples are to be found among asteroids & comets
  - Largest D/H ratios in AMMs (Duprat et al. 2010)
  - Largest $^{15}N/^{14}N$ ratio in a xenolith (Briani et al. 2009)

Gounelle *Elements* 2011